ENGINEERING GEOLOGY OVERVIEW OF MUNICIPAL SOLID WASTE LANDFILLS IN NORTHERN CALIFORNIA

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INTRODUCTION

Municipal solid waste landfills (landfills) are an extremely important and controversial part of the public infrastructure. Their performance depends to a large extent on natural geologic conditions, so engineering geology plays a key role in designing adequate controls to protect public health and the environment. As with other complex civil engineering works, the engineering geologist involved in landfill projects should be well versed in the specific geologic aspects of landfills, and in the environmental regulatory requirements that apply to them. Engineering geology is particularly important in landfill siting, design and construction, selection of earthen final covers, assessment of static and dynamic stability, environmental monitoring and control, and closure and postclosure maintenance. This paper provides an overview of these topics to assist engineering geologists new to landfill projects in northern California, and engineering geologists that desire more specific information for application to projects in northern California.

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Case histories of engineering geology work in existing landfills throughout northern California (Table 1) are helpful in addressing the challenges of new projects. As of January 1, 1999, there were approximately 185 active landfills statewide, of which approximately half are in northern California (for the purposes of this paper, northern California includes counties inclusive and north of Monterey, Kings, Tulare, and Inyo Counties). In October 1991 the number of active landfills statewide was approximately 270. This paper focuses on landfills that have received municipal solid waste since October 1991. Much of the information presented can also be applied to older sites, including those that may not have accepted municipal solid waste. Approximately 2,500 solid waste disposal sites statewide closed before October 1991, based on California Integrated Waste Management Board records.

Landfills in northern California are located in a diverse range of geologic settings (Harden, 1996; 2001, this volume), including the Basin and Ranges (Great Basin), Cascade Ranges, Coast Ranges, Great Valley (Central Valley), Klamath Mountains, Modoc Plateau, and Sierra Nevada.

The following topics are listed in the order of appearance in the paper, as a quick guide for finding material on the reader's topic of interest:

- Regulatory framework
- Landfill siting
- Design and construction
- Landfill containment systems
- Alternative earthen final covers
- Foundation and slope stability
- Seismic stability
- Seismic performance of landfills
- Environmental monitoring and control

County	Facility	Closure	Waste footprint (acres)	Geologic setting	Gas control	Ground Water monitoring & control	Liner system	Final cover system
Alameda	Tri-Cities	2002	115	Coast Ranges San Francisco Bay sediments	Active—Flare	Evaluation	UL	CCL
Alameda	Altamont	2007	206	Coast Ranges—terriary sedimantary—(great valley sequence)	Active—Flare	Corrective Action	UL-GM/CCL	CCL-GM/CCL
Alameda	Vasco Road	2016	222	Coast Ranges—terriary sedimentary—(great valley sequence)	Active—Flare	Detection	UL-GM-geocomposite/GM	CCL-GM/CCL
Amador	Buena Vista	2006	56	Sierra Nevada—foothills—tertiary sedimantary (Ione Fm.)	None	Detection	UL-CCL-GM/CCL	CCL-GM/CCL
Butte	Neal Road	2018	87	Cascade Range—intermediate volcanic/sediments (Tuscan Fm.)	None	Corrective Action	UL-CCL-GM/CCL	GM-GM/CCL or GM/CCL
Calaveras	Rock Creek	2032	57	Sierra Nevada foothills—metamorphic	None	Detection	CCL-GM/CCL-GM/GCL	GM/CCL
Colusa	Evans Road	1995	14	Great (Sacramento) Valley—(Tehama Fm.)	None	Detection	UL	CCL
Colusa	Stonyford	2059	4	Coast Ranges—alluvial	None	Detection	UL	CCL
Contra Costa	West Contra Costa	2000	160	Coast Ranges San Francisco Bay sediments	Active—Flare	Corrective Action	UL	CCL
Contra Costa	Acme Sanitary	2001	109	Coast Ranges San Francisco Bay sediments—Debris spread failure—1978	Active—Flare	Corrective Action	UL-CCL	CCL
Contra Costa	Contra Costa Pittsburg-GBF	1992	74	Coast Ranges—tertiary sedimentary—(great valley sequence)	Active—Flare Proposed	Evaluation	UL	CCL
Contra Costa	Keller Canyon	2098	271	Coast Ranges—tertiary sedimentary—(great valley sequence)—native slope failures—1997-98	Active—Flare	Detection	GM/CCL-FM/GCL (side)-GM/GCL/GM	GM/CCL
Del Norte	Crescent City	2002	23	Coast Ranges Northern coastal zone dune sands	Passive Venting	Detection	UL	GM
El Dorado	Union Mine	2015	40	Sierra Nevada foothills—metamorphic	Active—Flare	Detection	UL-GM/GCL-GM/GCL(side)	CCL-GCL-GM/CCL
Fresno	Chateau Fresno	1996	75	Great (San Joaquin) Valley	Active—Flare	Corrective Action	UL-CCL	GM
Fresno	Clovis	2029	55	Great (San Joaquin) Valley	None (Violation 10/99)	Corrective Action	UL-CCL-GM/CCL	CCL-GM/CCL
Fresno	Coalinga	2034	52	Coast Ranges—tertiary sedimentary	None	Detection	UL	CCL
Fresno	American Ave	2028	367	Great (San Joaquin) Valley	None	Detection	UL-GM/CCL	GM/CCL
Fresno	Orange Ave	2005	29	Great (San Joaquin) Valley	Active—Flare	Evaluation	UL	CCL or GM
Fresno	Chestnut Ave	1994	32	Great (San Joaquin) Valley	Active—Flare	Corrective Action	UL	GM
Glenn	Glenn County	2021	50	Great (Sacramento) Valley	None	Detection	UL	CCL
Humboldt	Cummings Rd	2007	38	Coast Ranges—tertiary sedimentary	Active—Flare (Violation 10/99)	Corrective Action	UL-GM/CCL-GM/GCL	GM
Inyo	Lone Pine	2055	27	Basin and Ranges—alluvial	None	Evaluation	UL	CCL
Inyo	Independence	2045	21	Basin and Ranges—alluvial	None	Detection	UL	CCL
Inyo	Bishop Sunland	2097	68	Basin and Ranges—alluvial	None	Evaluation	UL	CCL
Inyo	Shoshone	2074	5	Basin and Ranges—alluvial	None	Detection	UL	CCL
Inyo	Tecopa	2019	9	Basin and Ranges—alluvial	None	Detection	UL	CCL
Inyo	Furnace Crk.	1996	10	Basin and Ranges—alluvial	None	Detection	UL	Altern. Earthen
Kings	Avenal	2039	51	Coast Ranges—(Tulare Fm.)	None	Detection	UL	CCL
Kings	Hanford	1998	79	Great (San Joaquin) Valley	Active Flare (Violation 10/99)	Evaluation	UL	GCL
Kings	Mustang Hill-Not constructed	2040	41	Coast Ranges—(Tulare Fm.)	*NA	NA	GM/GCL	GM/GCL
Kings	Kettleman Hills	2025	43	Coast Ranges—tertiary sedimentary	None	Detection No beneficial use	GM/GM/CCL/GM/CCL	GM/CCL
Lake	Eastlake	2027	31	Coast Ranges—marine sedimentary—(great valley sequence)	None	Detection	UL-GM/CCL	GM-GM/GCL
Lassen	Bieber	1992	8	Cascade Ranges—volcanic/alluvial	None	Evaluation	UL	GCL
Lassen	Madeline	1997	<1	Basin and Ranges—alluvial	None	None	UL	GCL
Lassen	Ravendale	1997	<1	Basin and Ranges—alluvial	None	None	UL	GCL
Lassen	Bass Hill	2010	<10?	Basin and Ranges—alluvial	None	None	UL	No Closure Plan
Lassen	Westwood		<5?	Cascade Ranges—volcanic/alluvial	None	None	UL	No Closure Plan
Lassen	Sierra Army Depot	2032	32	Basin and Ranges—alluvial	None	Evaluation	UL	GM
Madera	Fairmead	2026	92	Great (San Joaquin) Valley	Active—Flare	Evaluation	UL-CCL-GM/CCL	CCL-GM/CCL-Altern. Earthen
Marin	Redwood	2039	195	Coast Ranges San Francisco Bay sediments	Active—Flare	Corrective Action	UL-GM/CCL	GM/CCL
Marin	West Marin	1998	15	Coast Ranges—marine sedimentary (Franciscan Fm.)	None	Evaluation	UL	CCL
Mariposa	Mariposa Co.	2081	40	Sierra Nevada—foothills—ultramafic intrusive serpentine	None	Detection	UL-GM/CCL	GCL-GM/GCL
Mendocino	Casper	1995	16	Coast Range—coastal zone marine terrace/Franciscan Fm.	Passive Venting	Corrective Action	UL	GM
Mendocino	Laytonville	1993	7	Coast Range—Marine Sedimentary—Franciscan Fm.	No	Detection	UL	GCL

Table 1. Northern California Subtitle D landfills (UL - unlined; CCL - compacted clay liner; GCL - geosynthetic clay liner; GM - geomembrane; Altern Earthen - monofill alternative earthen cover.).

County	Facility	Closure	Waste footprint (acres)	Geologic setting	Gas control	Ground Water monitoring & control	Liner system	Final cover system
Mendocino	South Coast	2015	5	Coast Range Marine Sedimentary (Franciscan Fm.)—Site is within San Andreas Fault Zone	No	Corrective Action	UL	CCL
Mendocino	City of Ukiah	2000	42	Coast Range Marine Sedimantary (Franciscan Fm.)	See Comment	Corrective Action	UL	CCL
Mendocino	City of Willits	1997	19	Coast Ranges—Marine Sediments (Franciscan Fm.)—native slope failure 1994-95	Passive Venting	Detection	UL-GM	GM
Merced	Hwy 59	2012	110	Great (San Joaquin) Valley	None (Violation 10/99)	Detection	UL-GM/CCL	CCL
Merced	Billy Wright	2009	40	Coast Ranges—marine sedimentary—(great valley sequence)	None (Violation 10/99)	Detection	UL	CCL
Modoc	Alturus	2009	<10?	Modoc Plateau—alluvial	None	Detection	UL	No Closure Plan
Modoc	Eagleville	1993	2	Basin and Ranges—alluvial	None	None	UL	GCL
Modoc	Fort Bidwell	1193	1	Basin and Ranges—alluvial	None	Detection	UL	GCL
Modoc	Lake City	1993	3	Modoc Plateau—alluvial	None	None	UL	GCL
Modoc	Cedarville	1993	2	Basin and Ranges—alluvial	None	None	UL	GCL
Mono	Walker	2260	10	Basin and Ranges—alluvial	None	Evaluation	UL	GCL
Mono	Bridgeport	2135	13	Basin and Ranges—alluvial	None	Evaluation	UL	GCL
Mono	Pumice Valley	2036	20	Basin and Ranges—alluvial	None	None	UL	CCL
Mono	Benton Crossing	2014	52	Basin and Ranges—alluvial	None	Evaluation	UL	CCL
Mono	Chalfant	2197	7	Basin and Ranges—alluvial	None	Evaluation	UL	GCL
Mono	Benton Crossing	2014	7	Basin and Ranges—alluvial	None	Detection	UL	GCL
Monterey	Lewis Rd	1999	14	Coast Ranges—tertiary sediments—dune sands	Active—Flare (Violation 10/99)	Evaluation	UL	GCL
Monterey	Johnson Canyon	2045	80	Coast Ranges—plutonic (granite)	Active—Flare (Violation 10/99)	Detection	UL-CCL-GM/GCL	GCL-GM/CCL
Monterey	Jolon Rd	2018	24	Coast Ranges—tertiary sedimentary	None	Detection	UL-GM/CCL	CCL-GM/CCL
Monterey	Crazy Horse	2008	72	Coast Ranges—tertiary sedimentary/dune sands	Active—Flare (Violation 10/99)	Corrective Action	UL-GM/CCL	CCL-GM
Monterey	Monterey Peninsula	2084	315	Coast Ranges—coastal zone dune sands	Active—Flare	Detection	GM/CCL-UL	GM/GCL
Napa	American Canyon	2000	97	Coast Ranges—San Francisco Bay sediments	Active—Flare	Corrective Action	UL	CCL
Napa	Clover Flat	2020	44	Coast Ranges—marine sedimentary	None	Detection	UL-GM/GCL	CCL-GM or GCL/CCL
Napa	Berryessa Garbage	1992	7	Coast Ranges—marine sedimentary	None	Detection	UL	CCL
Nevada	McCourtney Rd	1997	36	Sierra Nevada foothills—mafic/ultramafic intrusive	Active—Flare	Corrective Action	UL	GCL
Placer	Berry Street	1992	13	Great (Sacramento) Valley	None	None	UL	CCL
Placer	W. Regional	2016	231	Great (Sacramento) Valley	Active—Flare	Corrective Action	UL-GM/CCL	CCL-GM/CCL
Placer	Eastern Regional	1994	36	Sierra Nevada—plutonic (granodiorite)/alluvial	Active—Flare (Planned)	Detection	UL	CCL or GCL
Plumas	Portola	2022	8	Basin and Ranges—plutonic (granodiorite)	None	Detection	UL	CCL
Plumas	Gopher Hill	2016	13	Sierra Nevada—metamorphic	None	Corrective Action	UL	GM
Plumas	Chester	2045	28	Cascade Ranges—volcanic	None	Detection	UL	GM
Sacramento	Kiefer	2035	667	Great (Sacramento) Valley—tertiary sediments (Mehrten/Laguna Fms.)	Active—Flare	Corrective Action	UL-GM/CCL-GM/GCL	CCL-GM/CCL
Sacramento	Dixon Pit	1999	22	Great (Sacramento) Valley	Active—Flare (Violation 10/99)	Detection	UL	CCL
Sacramento	Sacramento City	1994	130	Great (Sacramento) Valley (ground water <5')	Active—Flare	Corrective Action	UL	CCL
Sacramento	L & D	2018	146	Great (Sacramento) Valley	Active—Venting	Corrective Action	UL-GM/CCL	CCL-GM
San Benito	John Smith Rd	2044	33	Coast Ranges—marine sedimentary—(great valley sequence)	None	Corrective Action	UL	CCL
San Joaquin	Austin Rd	2053	218	Great (Sacramento) Valley	Active—Flare	Corrective Action	UL-GM/CCL	CCL-GM/CCL
San Joaquin	French Camp	2010	60	Great (Sacramento) Valley	None	Evaluation	UL	CCL
San Joaquin	Harney Lane	1994	97	Great (Sacramento) Valley	Active—Flare	Corrective Action	UL	CCL
San Joaquin	Foothill	2054	50	Sierra Nevada—foothills—tertiary sedimentary (Mehrten Fm.)	None	Detection	UL-GM/CCL	CCL-GM/CCL
San Joaquin	Corral Hollow	1995	30	Great (Sacramento) Valley	None	Evaluation	UL	CCL
San Joaquin	Forward	2006	129	Great (Sacramento) Valley	None	Corrective Action	UL-CCL-GCL-GM/CCL	CCL-GM/GCL
San Joaquin	North County	2033	185	Great (Sacramento) Valley	None	Detection	GM-GM/GCL	CCL
San Mateo	Ox Mtn. (Corinda Los Trancos)	2023	184	Coast Ranges—plutonic (granodiorite) (San Andreas Fault—3 miles)	Active—Flare	Detection	UL-CCL-GM/CCL-GM/GCL (side)	CCL-GCL or GM
San Mateo	Hillside	2001	30	Coast Ranges—marine sedimentary—(Franciscan Fm.)	Active—Flare	Evaluation	UL-CCL-GM/CCL	GM/CCL
San Mateo	Burlingham	1994	41	Coast Range San Francisco Bay sediments	Active—Flare	Evaluation	UL	GCL-GM
Santa Clara	Pacheco Pass	2004	91	Coast Ranges—marine sedimentary Holocene fault (Coyote Lake segment of Calaveras Falut) within formerly proposed expansion	Active—Flare (Violation 10/99)	Corrective Action	UL-GM/CCL	Altern. Earthen-GM/CCL
Santa Clara	Shoreline-Mtn. View (Vista)	1993	150	Coast Ranges San Francisco Bay sediments	Active—Flare	Evaluation	UL-CCL	CCL

Table 1 (cont). Northern California Subtitle D landfills (UL - unlined; CCL - compacted clay liner; GCL - geosynthetic clay liner; GM - geomembrane; Altern. Earthen - monofill alternative earthen cover.).

County	Facility	Closure	Waste footprint (acres)	Geologic setting	Gas control	Ground Water monitoring & control	Liner system	Final cover system
Santa Clara	Sunnyvale	1994	92	Coast Ranges San Francisco Bay sediments	Active—Flare	Corrective Action	UL	CCL
Santa Clara	Palo Alto	2011	126	Coast Ranges San Francisco Bay sediments	Active—Flare	Detection	UL	CCL
Santa Clara	Newby Island	2016	313	Coast Ranges San Francisco Bay sedimens	Active—Flare	Detection	UL-GM/CCL	CCL-GM/CCL
Santa Clara	Kirby Canyon	2025	311	Coast Ranges—serpentine	Active—Flare	Detection	CCL-GM/CCL	GM/CCL
Santa Clara	Guadalupe	2020	115	Cascade Range—marine sedimentary/terriary volcanic (Franciscan/Temblor Fm.)	Active—Flare	Evaluation	UL-CCL-GM/CCL	CCL-GM/CCL-CCL (side)
Santa Clara	All Purpose	1993	25	Coast Ranges San Francisco Bay sediments	Active—Flare	Detection	UL	CCL
Santa Cruz	Santa Cruz	2037	58	Coast Ranges—marine sedimentary	Active—Flare	Corrective Action	UL-GM/CCL	CCL-GM/CCL
Santa Cruz	City of Watsonville	2023	51	Coast Ranges—coastal dune sands—terriary sediments	Active—Flare	Evaluation	UL-GM/GCL	CCL or GCl-GM/CCL
Santa Cruz	Ben Lomond	1994	24	Coast Ranges—tertiary sediments	Active—Flare	Corrective Action	UL	CCL
Santa Cruz	Buena Vista	2021	40	Coast Ranges—coastal dune sands—tertiary sediments	Active—Flare	Corrective Action	UL-GM/CCL	CCL-GM/CCL
Shasta	Redding (Benton)	1994	71	Great (Northern) Valley	Active—Flare	Detection	UL	CCL
Shasta	Anderson	2049	167	Great (Northern) Valley	Active—Venting	Detection	UL-GM/CCL	CCL-GM
Shasta	Intermountain	1993	4	Cascade Range—volcanic	None	Detection	UL	CCL
Shasta	West Central	2013	120	Great (Northern) Valley	None	Detection	UL-CCL-GM/CCL-GM/GCL	CCL-GM/CCL
Sierra	Loyalton	2032	29	Sierra Nevada—alluvial	None	Detection	UL	CCL
Siskiyou	McCloud	1995	13	Cascade Ranges—alluvial	None	Detection	UL	CCL
Siskiyou	Yreka	2109	54?	Cascade Range—volcanic/alluvial	None	Detection	UL	CCL
Siskiyou	Black Butte	2002	27	Cascade Range—volcanic/alluvial	None	Detection	UL	CCL
Siskiyou	Weed	1995	6	Cascade Range—alluvial	None	Detection	UL	Altern. Earthen
Siskiyou	Happy Camp	1996	3	Klamath Mtns.—metamorphic	None	Detection	UL	CCL
Siskiyou	Tulelake		9	Modoc Plateau—alluvial	None	Evaluation	UL	CCL
Siskiyou	Kelly Gulch	1994	1	Klamath Mtns.—metamorphic	None	Detection	UL	Altern. Earthen
Siskiyou	Cecilville	1994	1	Klamath Mtns.—metamorphic	None	Detection	UL	Altern. Earthen
Siskiyou	Lava Beds	1995	1	Modoc Plateau—volcanic	None	Detection	UL	Aletrn. Earthen
Siskiyou	New Tenant	1995	10	Cascade Range—volcanic	None	Detection	UL	Altern. Earthen
Siskiyou	Rogers Creek	1994	1	Klamath Mtns.—metamorphic	None	Detection	UL	Altern. Earthen
Siskiyou	Hotelling	1994	3	Klamath Mtns.—metamorphic	None	Detection	UL	Altern. Earthen
Solano	B & J Drop Box	2055	256	Great (Sacramento) Valley—alluvial—ground water <5'	None	Detection	UL-GM/CCL-GM/GCL (side)	CCL (side) Gm/CCL (top)
Solano	Rio Vista	1992	12	Great (Sacramento) Valley Sacramento River floodplain sediments	None	Detection	UL	CCL
Solano	Potrero Hills	2059	190	Coast Ranges—tertiary sedimentary	Active—Flare	Detection	CCL-GM/CCL-GM/GCL (side)	CCL-GM/CCL (Altern. Earthen test
Sonoma	Central	2014	172	Coast Ranges—marine sedimentary	Active—Flare	Corrective Action	UL-GM/GCL	GCL-GM/GCL
Sonoma	Annapolis	1995	5	Coast Ranges—marine sedimentary—(Francciscan Fm.)	None	Corrective Action	UL	GCL
Sonoma	Healdsburg	1993	27	Cascade Ranges—nonmarine sedimentary	None	Corrective Action	UL	CCL
Sonoma	Casa Grande	1993	9	Coast Ranges—fluvial	None	Detection	UL	CCL
Stanislaus	Fink Rd.	2019	216	Coast Ranges—marine sedimentary	None	Corrective Action	UL-CCL-GM/CCL	CCL-GM/CCL
Tehama	Red Bluff	2003	33	Great (Northern) Valley—alluvial	None	Detection	UL-GM/CCL	CCL-GM/CCL
Trinity	Weaverville	2004	13	Coast Ranges—alluvial	None	Corrective Action	UL	CCL
Tulare	Earlimart	1998	16	Great (San Joaquin) Valley	None	Detection	UL	GCL
Tulare	Exeter	2004	34	Great (San Joaquin) Valley	None	Detection	UL	CCL
Tulare	Teapot Dome	2005	71	Coast Ranges	None (Violation 10/99)	Detection	UL	CCL
Tulare	Woodville	2039	271	Great (San Joaquin) Valley	Active—Flare	Evaluation	UL-GM/GCL	GM
Tulare	Visalia	2019	127	Great (San Joaquin) Valley—alluvial	Active—Flare	Evaluation	UL	CCL
Tulare	Balance Rock	1998	10	Sierra Nevada—plutonic (granite)	None	Detection	UL	CCL
Tulare	Kennedy Meadows	2002	6	Sierra Nevada—alluvial	None	Detection	UL	CCL
Tuolumne	Big Oak Flat	2001	4	Sierra Nevada—foothills—metamorphic	None	Corrective Action	UL	CCL
Tuolumne	Central (Jamestown)	1996	16	Sierra Nevada—foothills—metamorphic	None	Corrective Action	UL-CCL	CCL
Yolo	Yolo Central	2020	347	Great (Sacramento) Valley—alluvial—ground water <5'	Active—Flare	Corrective Action	UL-GM/GCL-GM (side)	GM/CCL
Yolo	U C Davis	2032	53	Great (Sacramento) Valley	Active—Flare	Corrective Action	UL-CCL-GM/CCL	CCL-GM/CCL
Yuba	Beale AFB	1997	88	Great (Sacramento) Valley	Passive Venting	Detection	UL	CCL-GM
Yuba	Ponderosa	1995	10	Sierra Nevada—foothills—metamorphic	None	Corrective Action	UL	CCL
Yuba	Yuba Sutter Disposal, Inc.	1997	45	Great (Sacramento) Valley Yuba River floodplain sediments	Passive/active Venting	Corrective Action	UL-GM/CCL	CCL-GM/GCL (top)-GM (side)
Yuba	Yuba Sutter Disposal Area (YSDA)	1997	12	Great (Sacramento) Valley Yuba River floodplain sediments	None	None	UL	CCL-Altern. Earthen
Yuba	Ostrom Rd.	2038	221	Sierra Nevada—foothills—metamorphic	None	Detection	GM/CCL	GM/CCL

Table 1 (cont). Northern California Subtitle D landfills (UL - unlined; CCL - compacted clay liner; GCL - geosynthetic clay liner; GM - geomembrane; Altern. Earthen - monofill alternative earthen cover.).

- Groundwater monitoring and corrective action
- Corrective action and corrective action financial assurance
- Contamination of groundwater by landfill gas
- Surface water control
- Landfill gas monitoring and control
- Closure and postclosure maintenance and landuse
- Cost estimates for closure and postclosure maintenance
- Postclosure landuse
- Summary

REGULATORY FRAMEWORK

Landfills are regulated in California by a complex framework of federal, state, and local government codes and regulations (Table 2). These requirements control the application of engineering geology practice to landfill projects. Engineering geologists may also play a major role in preparing and coordinating permit applications, regulatory documents, and responses to comments from agencies and the public. An overall understanding of this regulatory framework is therefore essential in applying engineering geology practice to landfills.

National regulatory standards for landfills that operated on or after October 9, 1991 are contained in 40 CFR Part 258 (RCRA Subtitle D), promulgated by the United States Environmental Protection Agency (U.S. EPA). Implementation and enforcement of Subtitle D is primarily through approved state permit programs that must be equivalent or more stringent than Subtitle D. California is one of these approved states. U.S. EPA does not independently enforce Subtitle D where there is an approved state program. However, citizens may seek enforcement of Subtitle D independent of any state enforcement program by means of citizen suits in federal court under section 7002 of RCRA.

The California Integrated Waste Management Board (CIWMB) and State Water Resources Control Board (SWRCB) jointly implement California's Subtitle D program. The program is consolidated within California Code of Regulations Title 27 (27 CCR), Division 2. These regulations are also applicable in part to closed or inactive landfills that ceased receiving waste prior to the effective date of Subtitle D, and to solid and liquid waste disposal sites that exclude municipal solid waste. Air emission criteria for Subtitle D landfills are governed by the federal Clean Air Act New Source Performance Standards and Emission Guidelines. These requirements are implemented in California by local air districts (APCD/AQMD) and the California Air Resources Board (CARB).

In addition to the above the requirements, land use planning functions of local government can play a prominent role in the regulation of landfill projects and incorporation of public input. These functions primarily address implementation of the California Environmental Quality Act (CEQA), local codes and ordinances, and land use permits.

LANDFILL SITING

As in most areas of the country, siting new landfills in California is a daunting task because of pervasive negative public perception ("not in my backyard" or "NIMBY"). Siting projects for new landfills can expect to be legally challenged to the fullest extent and take 10 years or more and millions of dollars before waste is accepted or the project abandoned. The difficulty in siting new landfills is evidenced by the fact that only three new landfills became operational in northern California in the 1990's (Keller Canyon, Contra Costa County; North County, San Joaquin County; and Ostrom Road, Yuba County). Because of the difficulty in siting new landfills, most siting projects have focused on new regional landfills and lateral and vertical expansions of existing facilities.

New landfill design has recently concentrated on construction of regional landfills of immense capacity and proportions, called "megafills". Waste is transported to these facilities mainly by rail haul and large waste transfer trucks. Two "megafills" in southern California have recently been permitted but are not yet constructed. They include the Mesquite Regional Landfill (Imperial County) and the Eagle Mountain Landfill (Riverside County). The Mesquite Landfill has a total design capacity of 1,100,000,000 cubic yards. By contrast, the largest landfill in northern California, Kiefer Landfill (Sacramento County), was recently permitted for expansion to a total capacity of 127,000,000 cubic yards.

The Regional Water Quality Control Board (RWQCB) classifies landfill waste management units for siting purposes according to their ability to contain wastes. Class III landfill units typically allow disposal of municipal solid waste (nonhazard-

Description	Regulatory citation	Implementing agency
RCRA Subtitle D Program		
General scope and applicability	27 CCR, Chapter 1, Article 1	CIWMB & SWRCB
Waste classification	27 CCR, Chapter 3, Subchapter 2, Article 2	SWRCB
Waste unit/facility/site classification and siting	27 CCR, Chapter 3, Subchapter 2, Article 3	SWRCB & CIWMB
Waste unit construction standards	27 CCR, Chapter 3, Subchapter 2, Article 4	SWRCB
Water quality monitoring and response	27 CCR, Chapter 3, Subchapter ?, Article 1	SWRCB
Operating criteria	27 CCR, Chapter 3, Subchapter 4	CIWMB
Landfill gas monitoring and control	27 CCR, Chapter 3, Subchapter 4, Article 6	CIWMB
Closure and postclosure maintenance standards	27 CCR, Chapter 3, Subchapter 5	SWRCB & CIWMB
Waste discharge requirements (WDRs) and solid waste facilities permit (SWFP)	27 CCR, Chapter 4, Subchapter 3	SWRCB (RWQCB) & CIWMB (Local Enforcement Agency)
Closure and postclosure maintenance plans	27 CCR, Chapter 4, Subchapter 4	CIWMB & SWRCB
Financial assurances (closure, postclosure, operating liability, and corrective action)	27 CCR, Chapter 6	CIWMB & SWRCB
Air emission requirements		
New Source Performance Standards (NSPS) and Emissions Guidelines (EG) for municipal solid waste landfills	Rules adopted by individual APCD/AQMD (e.g. Regulation 8 Rule 34 of Bay Area AQMD and Rule 1150.1 of South Coast AQMD)	APCD/AQMD & CARB
Permits to construct and operate	Rules adopted by individual APCD/AQMD	APCD/AQMD
Other common requirements		
Evaluation and public notification of environmental impacts	California Environmental Quality Act (CEQA)	Local or State lead (In most cases City or County)
Local land use permits	Local codes and ordinances	City or County
Stormwater and discharges to surface waters	National Pollutant Discharge Elimination System (NPDES)	SWRCB
Wetlands protection	Federal Clean Water Act SWRCB Resolution 93-62 California Fish and Game Code	U.S. Army Corps of Engineers SWRCB & California Department of Fish and Game
Endangered plants and animals	Federal Endangered Species Act California Fish and Game Code	U. S. Fish & Wildlife Service & Cal. Department of Fish & Game

Table 2. Regulatory framework for California landfills.

ous solid waste, inert solid waste, and sludges from household, commercial, and industrial sources). Class II units allow disposal of designated wastes determined by the RWQCB to be nonhazardous wastes, but which may contain soluble pollutants that could be released in concentrations exceeding applicable water quality objectives and could cause degradation of waters of the state. Designated solid wastes are determined on a site-specific basis and typically include industrial ashes, sludges, contaminated soils, and hazardous wastes granted a variance. Depending on site-specific permit requirements, Class II units may include solely designated wastes, or a mixture of designated, nonhazardous, and municipal solid waste. Class II landfills in northern California accepting municipal solid waste include Altamont (Alameda County), B&J Drop Box (Solano County), Buena Vista (Amador County), Forward (San Joaquin County), Keller Canyon (Contra Costa County), Ostrom Road (Yuba County), Rock Creek (Calaveras County), and West Contra Costa (Contra Costa County). Class II units may also be surface impoundments for containment of liquid wastes such as landfill leachate. Each classification has separate siting standards, with Class II being more stringent than Class III. Siting criteria in California's Subtitle D program are summarized in Table 3.

Description	Class III landfills	Class II landfills
Geologic setting	Shall not be located within areas of potential rapid geologic change unless the RWQCB find that containment structures preclude failure	Same as Class III
Foundation	Shall provide support capable of withstanding hydraulic pressure gradients to prevent failure due to settlement, compression, or uplift	Same as Class III
Ground rupture	Shall not be located on known Holocene fault	200' Setback from known Holocene fault
Seismicity	Shall withstand the effects of seismic ground motions resulting from at least the Maximum Probable Earthquake (MPE)	Shall withstand the effects of seismic ground motions resulting from at least the Maximum Credible Earthquake (MCE)
Groundwater separation	Shall ensure wastes will be a minimum of 5-feet above highest anticipated elevation of groundwater unless engineered alternative exemption granted	Same as Class III
Flooding and tidal waves	Shall prevent inundation or washout due to floods with a 100-year return period and tsunamis, seiches, and surges	Same as Class III
Airport safety	Must demonstrate no bird hazard to aircraft (only municipal solid waste (MSW) landfills)	Same as Class III
Wetlands	Shall not be located in wetlands unless protected and impacts mitigated in accordance with Clean Water Act and State wetlands laws (Incorporated by reference from 40 CFR 258.12 & Section 404 of Clean Water Act)	Same as Class III

Table 3. Summary of siting criteria for California landfills (27 CCR, Chapter 3, Subchapter 2, Article 3).

The siting of new landfills and expansions involves a team of experts from multiple disciplines, including engineers, planners, environmental specialists, engineering geologists, and lawyers. Landfill siting studies typically include extensive site-specific geologic, geotechnical, and hydrogeologic exploration and characterization, not only for compliance with regulatory criteria and environmental impact analysis, but also as a basis for planning economic landfill design, construction, operation, and environmental monitoring and control. Table 4 provides a summary of engineering geology aspects of landfill siting studies.

DESIGN AND CONSTRUCTION

Design and construction of landfills involves engineers, engineering geologists, and contractors to prepare and implement landfill design plans and specifications. As part of the design and construction team, engineering geologists are primarily involved in the assessment of geologic and hydrogeologic site conditions, evaluation of soil or natural earthen material borrow sources, modeling the performance of these materials in containment system design, and in the evaluation of geologic factors for static and seismic stability analysis.

A major task of the engineering geologist is the assessment of the geologic and hydrogeologic site conditions with respect to the proposed landfill. This assessment is highly detailed and includes elements such as:

- Description and mapping of geologic units, stratigraphic units, and structural features (bedding, fractures, joints, faults) within one mile of the landfill
- In-grading geologic mapping
- Description of faulting and seismicity of the landfill site and adjacent region within 100 kilometers (62 miles) of the landfill
- Field determination of the hydraulic parameters of the soil or rock adjacent to the landfill (e.g., hydraulic conductivity, transmissivity)
- Documentation of the hydrogeology of the site, including compilation of recorded groundwater and tidal fluctuations
- Documentation of groundwater and surface water quality background
- Location of off-site landfills and other sites that may be potential sources of degraded groundwater or landfill gas

Engineering geologists routinely are in charge of locating and assessing borrow sources for soils that meet the engineer's specifications for construction and operation of the landfill.

Borrow sources may be developed for materials to be used as low permeability earthen components of

Aspect	Task description	References
Geology	Compile and evaluate existing geologic mapping data and reports for study area. Map geology in the field utilizing base maps, aerial photography, and remote sensing imagery as appropriate. Prepare geologic maps, cross sections, and reports for final presentation	California Division of Mines and Geology U. S. Geological Survey ASTM (1997) California Board of Registration for Geologists and Geophysicists
Geologic hazards	Compile and evaluate existing geologic hazard data for study area. Conduct field investigations as necessary to confirm and supplement existing data. Prepare reports for final presentation	California Division of Mines and Geology U. S. Geological Survey USEPA (1993a)
Faulting and seismicity	Conduct literature review of seismic and fault mapping studies for study area. Determine appropriate seismic parameters (MPE, MCE, ground acceleration). Evaluate potential occurrence of Holocene faults in study area or adjacent to study area if necessary by trenching, mapping, geophysical methods, and soil dating. Prepare reports for final presentation	California Division of Mines and Geology U. S. Geological Survey Richardson, et al. (1995) USEPA (1993a) California Board of Registration for Geologists and Geophysicists
Engineering properties of geologic materials	Conduct field sampling and evaluation utilizing borings, trenches, test pits, geophysical methods, and laboratory analyses to establish geologic material properties for study area (lithology, distribution, geotechnical properties, and applicability for use as construction materials). Conduct specialized studies as necessary on construction material sources and foundation and slope stability issues. Prepare reports for final presentation	ASTM (1997) TRB (1996) U. S. Department of Navy (1982) California Board of Registration for Geologists and Geophysicists
Hydrogeology	Conduct literature review and field investigation of ground water flow chacteristics and quality utilizing test borings, monitoring wells, aquifer test methods, and geophysical methods. Conduct modeling and tracer studies as necessary for specialized studies on environmental fate, transport, and hydraulic impacts. Prepare reports for final presentation	ASTM (1997) USEPA (1993a), (1993b), & (1986) U. S. Geological Survey California Department of Water Resources California Board of Registration for Geologists and Geophysicists
Baseline monitoring	Prepare and implement monitoring programs for baseline ground water and vadose zone quality and physical characteristics. Prepare reports for final presentation	ASTM (1997) USEPA (1993a), (1993b), & (1986)
Technical assistance and expert testimony	Review comments from public and agencies on engineering geology issues. Prepare responses and conduct testimony as necessary for administrative and court hearings and records	

Table 4. Engineering geology aspects of landfill siting studies.

liner and final cover systems, construction fill, rock and aggregate, and daily and intermediate cover. The availability of low cost soils can have a profound impact on the cost of building, operating and closing a landfill. If soils with properties appropriate for landfill construction or operation are not obtainable near the landfill, then other off-site sources need to be considered, or geosynthetic materials might need to be used to help replace the amount of soil needed for a particular landfill activity.

Borrow source evaluations will typically begin with the preliminary location of potential on-site and off-site sources for the specified materials. The potential on-site source is mapped and tested for the quality and quantities of soils that are being sought for use in the project. The assessment may include logging and sampling of boreholes, trenches, and test pits, in addition to testing of samples for geotechnical properties and conducting rippability seismic surveys if the soils are indurated. Borrow source evaluations also determine the types and amounts of the required materials available, and the quantity of overburden that must be removed to extract the target materials. Reclamation plans of excavations must also be implemented. Guidance for the evaluation of engineering properties of earthen materials is provided in U.S. Department of Navy (1982), U.S. EPA (1993b), TRB (1996), and ASTM (1997). Recommended guidance regarding assessment and development of borrow material sources specifically for landfills is also provided in Bolton (1995).

The role of engineering geologists regarding slope, foundation, and seismic stability aspects of design is to confirm the stability of the engineer's design in light of the specific geology of the substrate, and to propose design soil strength parameters for earthen construction materials to ensure that the containment structures are stable. Guidance for landfill seismic stability evaluations is provided in Kavazanjian (1999, 1998), Anderson (1997), Richardson et al. (1995), and U.S. EPA (1993a). Engineering geologists can also play an integral part in the earthquake preparedness planning for the site.

The engineering geologist may also be called upon to collect background data about the natural occurrence of methane and other gases (organic soils and sediments, oil or gas fields, asphalt seeps, and geothermal areas), and to establish a method to determine the differences between landfill gas and naturally occurring gases.

Landfill containment systems

The requirement for landfill liners is relatively recent, so the majority of landfills in northern California are unlined; however, active disposal areas are shifting to lined areas as existing footprints become full (Table 1). Subtitle D design criteria include performance and prescriptive requirements for landfill liner systems for new units and lateral expansions. The Subtitle D prescriptive design is a composite liner including an upper component with a minimum 30-mil thick (60-mil if HDPE) flexible geomembrane liner (GM) in direct contact with a lower component of at least two-feet of compacted earthen material (compacted clay liner or CCL). The CCL component must have a hydraulic conductivity of less than or equal to 1×10^{-7} cm/sec. Site-specific performance, or risk based alternative liner designs, are an option for approved Subtitle D programs. Engineered alternatives to prescriptive standards are allowed in California under 27 CCR section 20080(b). However, alternatives to the prescriptive composite liner design have been approved only for very few sites in California, except for side-slope liners and replacement of part, or all, of the CCL component by a geosynthetic clay liner (GCL).

The performance requirements for final cover systems are to minimize erosion and infiltration, and to have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils to avoid the "bathtub effect". The "bathtub effect" refers to the concern that excessive infiltration over exfiltration at the base of the landfill would allow pollutants to concentrate in ponded leachate. The leachate would then pose a much higher threat to groundwater if a leak were to occur.

The prescriptive final cover design for an unlined landfill in California includes, from bottom to top, a minimum two feet thick foundation layer, a minimum one foot compacted clay infiltration-control layer with a hydraulic conductivity no greater than 1×10^{-6} cm/sec, and a minimum one foot earthen layer to resist erosion (this layer must be capable of sustaining plant growth). For a lined landfill, the prescriptive final cover must additionally have a geomembrane on top of the compacted clay infiltration-control layer. Although not specified in the regulations, many final covers include a drainage layer between the erosion and infiltration-control layers for slope stability purposes. A gas collection layer may also be required, especially when a geomembrane is used and there is no active gas control system. Final cover system design guidance is provided in Koerner and Daniel (1997) and U.S. EPA (1993a).

Geosynthetic materials have only recently been utilized on a widespread basis in northern California as landfill base liner and final cover components. In contrast, compacted clay liners started to be widely used in northern California in the late 1980's, and standard clay material sources (Table 5) and construction practices are now relatively well-established (Walker and Rosenbaum, 1995). GCL products are now becoming a cost-effective alternative for compacted clay liners because of lowering costs and more experience and comfort in the use of these products by engineers, regulators, and contractors.

Construction Quality Assurance (CQA) programs are required under California's Subtitle D program to ensure that construction of landfill containment systems is performed in accordance with approved design plans and specifications. The CQA plan must incorporate standard geotechnical testing of fills and field permeability testing of compacted clay components to establish correlation between index testing and the design hydraulic conductivity. Final documentation and certification must also be submitted to ensure that construction was in accordance with approved design criteria, plans, and specifications. Guidance for CQA of waste containment facilities is provided in U.S. EPA (1993c, 1994).

Alternative earthen final covers

There are increasing doubts about the performance of final cover systems using compacted clay infiltration-control layers, especially in arid and semi-arid areas where desiccation cracking is likely to occur. Clay-based final cover systems can also be expensive if borrow sources cannot be developed locally. Therefore, alternative earthen materials that use the natural moisture retention properties of soils and vegetation are rapidly gaining acceptance. Monofill alternative earthen final cover systems are constructed using a single soil type formed by a

Material source	Examples of landfills where used	Material characteristics (not for design purposes)
Ione Formation; commercial quarries; Amador County	Red Hill (Calaveras) Union Mine (El Dorado) Kiefer (Sacramento)	CL; PI =15 - 29%; ϕ = 19; c =150; K = 5.6 x 10^{-8} cm/sec (SDRI);
Commercial quarries and on-site (Ione Formation to Pleistocene); Placer County	Sacramento City (Sacramento) Western Regional (Placer)	CL; PI =12 -19%; K = <1 x 10^{-6} cm/sec (DRI);
San Francisco Bay muds; on-site and off-site sources; San Francisco Bay area	Acme (Contra Costa) American Canyon (Napa) All Purpose (Santa Clara)	CH-MH; PI 40 - 65 + %; ϕ = 8.5; c = 250; K = 3.5 x 10^{-8} cm/sec;
On-site soils Coast Ranges (Great Valley Sequence)	Altamont (Alameda) Potero Hills (Solano)	CH-CL; PI = 23 - 45%; K = <5 x 10^{-8} cm/sec (SDRI);
On-site soils (Victor Formation); Yuba County	Ostrom Rd; Ponderosa; YSDA; (Yuba)	CL; PI = 9 - 18%; ϕ =12.5; c = 890; K = 1 x 10^{-7} cm/sec;
On-site soils with admixture	Benton (Shasta) Harney Lane (San Joaquin)	Blended <5% commercial bentonite (Benton) In-place mixing of up to 30% Ione Clay (Harney Lane) Both required to achieve; K = <1 x 10^{-6} cm/sec (SDRI)

Table 5. Examples of Northern California low permeability earthen materials.

mixture of silt and sand with some clay. These final cover systems are also called evapo-transpiration (ET) covers and can include separate layers and capillary barriers. The earthen materials used are of higher hydraulic conductivity and are placed at lower density than the prescriptive standard compacted clay liners. Because of cost savings, ease of maintenance, and effectiveness, alternative earthen covers are also being considered in specific situations as a replacement for GM-based systems.

The Desert Research Institute is currently conducting an Alternative Cover Assessment Project (ACAP) funded primarily by U.S. EPA. This project will measure the field performance of alternative earthen final covers, improve numeric modeling capabilities and monitoring methods, and provide regional design guidance. Coupled with other ongoing research and pilot project efforts, this project is intended to provide performance data for alternative earthen cover options, so they can be approved where appropriate. At the present time, test pads are being required at most sites in California to demonstrate these systems on a site-specific basis. Two basic types of test pad monitoring programs are currently used. One type includes *in situ* moisture monitoring probes to measure the time distribution of moisture movement through the test pad (time domain reflectometry (TDR) or capacitance systems). The other type uses a pan lysimeter system to measure percolation through the test pad. In both cases, site-specific precipitation data is collected and the system is monitored over multiple seasons. Computer models (e.g. HELP, LEACHM, UNSAT-H) are normally used to design the test pad and to process the field data to demonstrate acceptable performance. Alternative earthen final cover test pad projects are currently being conducted in northern California at the Potrero Hills Landfill, Solano County (TDR system) and Kiefer Road Landfill, Sacramento County (pan lysimeter system). Further information on this developing technology is provided in Reynolds et al. (1997) and Lass et al. (1997).

Foundation and slope stability

Foundation and slope stability of landfills became a recent focus of concern as a result of a massive failure, in March 1996, of the Rumpke Sanitary Landfill in Ohio. Kenter et al. (1997) concluded that a combination of the height and angle of the fill slope, buildup of leachate in the waste, excavation at the toe, and possibly saturated soils and weathered shale bedrock may have led to a deep foundation failure at the bottom of the waste mass. Schmucker and Hendron (1998) and Evans and Stark (1997) provide additional information and debate on the causes and lessons learned from the Rumpke failure. The Rumpke Landfill failure should heighten awareness of potential landfill failures in northern California, especially in sites with weak foundation materials, such as the San Francisco Bay muds, and in landslide-prone soils of the Coast Ranges. Although not at the catastrophic level of the Rumpke Landfill failure, other slope and foundation failures have occurred at northern California landfill sites. A review of two of these cases may be useful as precedents for addressing future stability problems.

Figure 1. Aerial photograph of the Acme Landfill failure in 1978. Failure scarp and toe can be seen toward the left side of the photograph.

In 1978 a failure occurred within the Acme Landfill, Contra Costa County, resulting in spreading of waste and soils onto an adjacent wetlands area (Figure 1). The failure was attributed to rapid loading of waste on weak San Francisco Bay mud. The rate of loading was modified to prevent additional failures, and inclinometers were installed in order to monitor movement in the waste mass. The landfill has remained stable ever since.

During abnormally high rainfall in 1997-98, the Keller Canyon Landfill, Contra Costa County, experienced a major slope failure within Tertiary sedimentary rocks (Eocene Markley Formation) of the Coast Ranges (Figures 2 and 3). The failure was interpreted as a wedge-like failure reactivated from an ancient landslide. The failure encroached on a planned liner expansion area that had to be delayed and redesigned. The recommended remedial alternative was to partially remove the slide and construct an earthfill toe buttress. The total excavation removed nearly 2.5 million cubic yards of landslide material and the redesign project has been completed successfully. Detailed description of the geology of the failure area and resultant remediation and liner design changes is provided in BFI (1998).

Seismic stability

Under Subtitle D, seismic design may be based on either the peak horizontal ground acceleration from U.S. Geologic Survey hazard maps for seismic impact zones, or be based on a site-specific analysis. Seismic impact zones are areas with 10% or greater

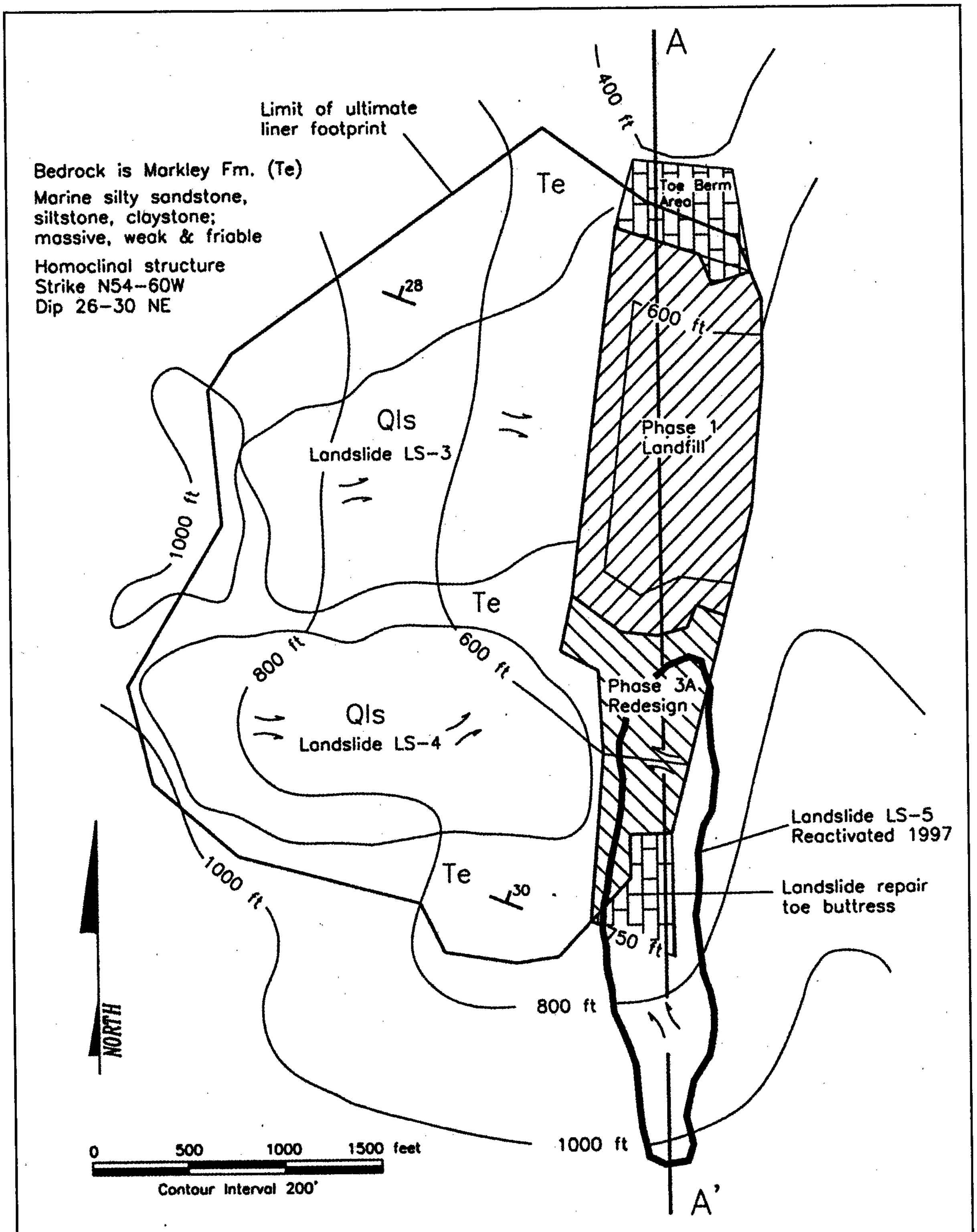

Figure 2. Engineering geology map of Keller Canyon Landfill (adapted from BFI, 1998).

probability that the peak horizontal acceleration in lithified material will exceed 0.10 g in 250 years. The hazard maps indicate design accelerations over 0.80 g in areas of northern California, which would make landfill design in these areas difficult, if not impossible. Therefore, seismic stability analysis of northern California Class III landfills is mainly based on site-specific deterministic evaluations

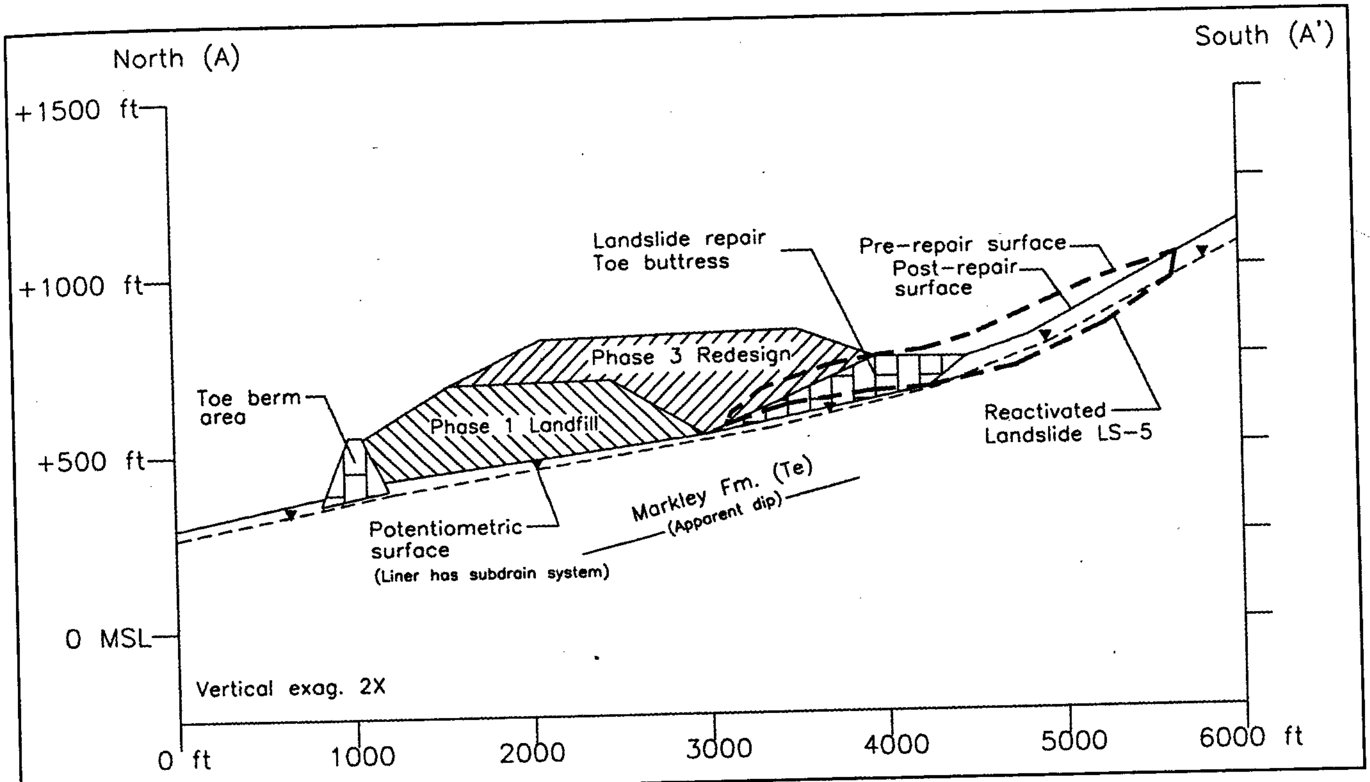

Figure 3. Section A - A' showing the toe buttress constructed for landslide repair (adapted from BFI, 1998).

based on the Maximum Probable Earthquake (MPE). The MPE is the maximum earthquake that is likely to occur during a 100-year interval, and should not be less than any historic earthquakes for the fault segment. Use of the MPE has been subject to considerable debate in California. In most cases, the peak ground accelerations from the MPE are less than those derived from hazard maps or the Maximum Credible Earthquake (MCE). However, U.S. EPA has determined that the use of the MPE in California satisfies the Subtitle D requirement for site-specific analysis (Anderson, 1997).

The state-of-practice of landfill seismic stability analysis in California is first to characterize the appropriate seismic source and then evaluate the ground motions. The engineering geologist characterizes potential seismic sources by first compiling and reviewing available information on historic earthquakes and Holocene faults in proximity to the site. Field investigations may be necessary and could include mapping, trenching, geophysical surveys, and microseismicity surveys.

Peak horizontal ground acceleration (PHGA) in lithified material is estimated using acceleration attenuation relationships that correlate earthquake magnitude, fault style, distance to source, and local site conditions. In some cases site-specific dynamic response analysis is performed using computer programs such as SHAKE. Dynamic analysis is then performed using the highest estimated PHGA. Response spectra may also be used for the dynamic analysis. The Newmark method is then applied to determine permanent seismic deformations along representative cross-sections analyzed for static and pseudo-static stability. More sophisticated site-specific analyses (e.g. finite element and three-dimensional analyses, liquefaction susceptibility assessment, vertical acceleration settlement analysis) are done on a case-by-case basis. Allowable deformations to maintain landfill containment must be demonstrated on a site-specific basis. Kavazanjian (1999) provides generic guidelines for allowable seismic displacements for landfills. Table 6 shows examples of design earthquakes and summaries of stability analyses for selected northern California landfills.

Seismic performance of landfills

Krammer (1998) defines lifeline facilities as a network of facilities that provide the services required for commerce, communication, sanitation, and care of public health, which can be found in virtually any developed area. Lifeline facilities include

Landfill & County	Design earthquake characteristics	Results of stability calculations
Altamont (Alameda)	7.0 MCE; 0.46g; Greenville fault; 4 miles	<1ft. dynamic displacement determined acceptable
Palo Alto (Santa Clara)	8.25 MPE; 0.49g; San Andreas fault; 8 miles	Minimum FS static- 1.6; 2 to 3 ft. dynamic displacement determined acceptable for final cover (unlined site) Localized potential for liquefaction
Potrero Hills (Solano)	6.4 MPE; 0.33g; Winters-Dunnigan Hills fault	Minimum FS static- 1.5; <0.5 ft. dynamic displacement (not significant)
Kiefer (Sacramento)	5.7 MPE; 0.20g; Bear Mtns. (Foothill) fault; 10 miles	Minimum FS static- 1.55; 0.25 ft.dynamic displacement (not significant)
Cummings Road (Humboldt)	7.5 MPE; 0.52g; Little Salmon fault 8.4 MPE; 0.50g; Cascadia subduction zone	Minimum FS static- 1.5; Operator determined <0.33 ft. dynamic displacement (not significant); Department of Water Resources determined dynamic displacement up to 5 ft.
Acme (Contra Costa)	6.0 MPE; 0.59g; Concord fault; <1 mile	Minimum FS static- 1.55; 0.5 to 3 ft. dynamic displacement determined acceptable for final cover (unlined to CCL-lined site); potential for liquefaction

Table 6. Selected design earthquakes for Northern California landfills.

landfills and hazardous waste landfills, and are therefore an element of seismic planning.

The standards and accepted practices for seismic design and construction of facilities, and emergency planning and response, are reevaluated after every major earthquake. The performance of landfills during earthquakes is an area of active interest and research because assessing and repairing liner damage is very difficult and because of the need for safe areas to dispose of disaster debris and waste.

In 1995 the American Society of Civil Engineering published a book entitled *Earthquake Design and Performance of Solid Waste Landfills*. This publication contains many key reference papers on landfill performance during earthquakes up to and including the Northridge earthquake of 1994. Landfill seismic performance assessment came into its own after the 1987 Whittier earthquake and investigation of the OII Landfill in Los Angeles County. The OII Landfill continues to provide valuable information on landfill seismic response from strong motion instruments installed in 1987. After the 1989 Loma Prieta earthquake, investigators reported no significant damage to landfills (Orr and Finch, 1990). This was the first large earthquake in which landfills were subsequently evaluated, although those landfills did not reflect the complex containment designs currently required. Likewise, no significant damage was reported at landfills as a result of the 1992 Landers earthquake. Landfills utilizing geosynthetic liner components were first evaluated for seismic performance and damage from strong ground motions from the Northridge earthquake of 1994 (Augello et al. 1995). After the Northridge earthquake, Matasovic et al. (1998) developed a reference chart describing the relative level of damage that a landfill had experienced. In September 1994, a large earthquake offshore of northern California (Cape Mendocino earthquake) coincided with differential settlement of a toe buttress under construction at the Cummings Road Landfill, Humboldt County. The location of the cracking and settlement was well correlated with the outer limits of the waste. The buttress was promptly repaired and no significant damage has occurred since.

The major seismic performance problem to date with landfills has been the loss of power to the landfill gas control systems and damage to gas control laterals and headers. This has occurred after each major earthquake in California with a landfill gas control system operating near the epicenter. Power to the systems was restored shortly after it was restored to the local power grid, and lateral and header piping systems have been promptly repaired. In no case was the loss of power or damage to laterals and headers the cause for shutting down a landfill for an extended period of time. Some landfills have closed temporarily after an earthquake, but only as a precautionary measure, to be reopened shortly after site inspection was completed.

In California, few composite-lined landfills, and none capped with geosynthetic components, have been subjected to high (greater than 0.3 g PHGA) ground motions. However, with the recent increase in complex geosynthetic-based designs in landfill construction there is a continued need to evaluate the performance of landfills in future seismic events. A guide for conducting investigations after an earthquake is provided in EERI (1996).

ENVIRONMENTAL MONITORING AND CONTROL

Pollution from landfill leachate, gas, and sediment is a major concern at landfill sites. Because of the controlling influence of geologic conditions on environmental fate and transport, engineering geology is important in the design, construction, and implementation of monitoring and response programs. These programs must ensure that releases to the environment are promptly detected and controlled.

Groundwater monitoring and corrective action

Groundwater monitoring and response protocols in California's Subtitle D program include detection of a potential release (detection monitoring), assessment of any statistically significant evidence for release over background (evaluation monitoring), and evaluation and implementation of corrective action measures. Unsaturated zone monitoring is also required for early leak detection. Based on a survey conducted by SWRCB in spring 1999, groundwater monitoring programs for northern California landfills included detection monitoring at 68 sites, evaluation monitoring at 25 sites, and corrective action at 37 sites (the survey also disclosed 11 sites where no monitoring was being conducted) (Table 1).

Groundwater monitoring and response programs for individual California landfills cannot be transferred as a "boilerplate" from one site to another, but the experiences and track record of other sites can provide a basis for the design of new programs. Evaluation and corrective action programs especially need to be prepared on a site-specific basis and may require multiple phases of remedial investigation, monitoring well construction, specialized sampling and analysis, aquifer characterization, groundwater flow modeling, and engineering feasibility studies.

In addition to RWQCB file records of specific sites, a plethora of sources of information and guidance documents are available on groundwater monitoring and response programs. Selected recommended references include Hudak (1998), ASTM (1997, 1996), SWANA (1997b), and U.S. EPA (1993a, 1993b). An excellent compilation of California water quality goals and standards can be found in CVRWQCB (1998). Statistical methods in groundwater monitoring are continually evolving and subject to ongoing debate. Several recent journal articles have reevaluated the application of statistical methods to groundwater detection monitoring (Pittenger, 1998; Gibbons, 1998; Loftis et al., 1999).

Under California' Subtitle D program, the term "water quality protection standard" is used to encompass the list of constituents of concern, the concentration limits, the specified point of compliance and all monitoring points. The "water quality protection standard" is site-specific and is prescribed in permits issued by the RWQCB (e.g., waste discharge requirements [WDRs] and monitoring and reporting programs [M&RPs]). The constituents of concern (COCs) include "all waste constituents, reaction products, and hazardous constituents that are reasonably expected to be in or derived from waste contained in the unit". COCs are included as a prescribed list of contaminants for each landfill drawn from Appendices I and II of Subtitle D. COCs must be monitored at least once every five years. The default concentration limits are background levels. For detection monitoring, the operator must specify monitoring parameters for RWQCB approval that are a reliable indicator of a release from the unit. The point of compliance for groundwater is defined as "...a vertical surface located at the hydraulically downgradient limit of the waste unit that extends through the uppermost aquifer underlying the unit" (27 CCR Division 2, Subdivision 1 Chapter 2, Article 2).

Subtitle D allows groundwater monitoring to be suspended if the owner or operator demonstrates that there is no potential for migration of hazardous constituents to the uppermost aquifer ("no migration" petition). California's program in practice does not reflect the full flexibility afforded by Subtitle D and it is difficult to obtain regulatory approvals for variances from prescribed programs. For example, risk-based corrective action programs where clean-up levels are above background are of considerable nationwide interest but have not gained acceptance in California. California's Subtitle D program does allow for site-specific approval of a concentration limit greater than background, but only when the RWQCB finds that it is technologically or economically infeasible to achieve background and that the constituent will not pose a substantial present or potential hazard to human health or the environment. In practice this approval has been difficult to obtain.

Corrective action and corrective action financial assurances

California's Subtitle D program requires financial assurances for known and "reasonably foreseeable" releases. "Reasonably foreseeable" is not defined and there are few landfills statewide with approved cost estimates. Examples where corrective action scenarios and cost estimates have been submitted to meet this requirement in northern California include Kiefer Landfill, Sacramento County ($800,000), B&J Landfill, Solano County ($869,040), and Union Mine Landfill, El Dorado County ($211,640). Corrective action measures implemented at northern California landfills include groundwater pump-and-treat systems, landfill gas control systems, leachate collection and treatment systems, and final closure.

Contamination of groundwater by landfill gas

Volatile organic compounds (VOCs) are commonly detected groundwater contaminants at landfills and are common trace components of landfill gas. Transport of VOCs from landfill gas to groundwater can occur by direct contact or indirectly as a dissolved phase in leachate or gas condensate. Landfill gas is increasingly being considered as the principal source of VOCs detected in groundwater at landfill sites, so gas control systems are commonly being used for groundwater corrective action programs. Baker (1998) reported on groundwater assessments of landfills in which 90 per cent were shown to have landfill gas as a source of VOCs. Tuchfeld et al. (1998) applied geochemical modeling methods to determine sources of groundwater VOC contamination from landfill gas. Desrocher and Lollar (1998) and Mohr et al. (1992) used isotopic methods to evaluate landfill gas and other potential sources of groundwater contamination.

In northern California extensive studies of the Kiefer Landfill concluded that landfill gas was the dominant source of VOCs (Sacramento County, 1998; Maxfield and Vanderbilt, 1997). Figure 4 is a cross section showing the extent of landfill gas migration and VOC contamination in groundwater at the Kiefer Landfill. Corrective action measures implemented at Kiefer Landfill include a groundwater pump-and-treat system, and an active landfill gas extraction and flare system. A soil vapor extraction system was planned but was not implemented because the operator contends that the landfill gas control system has successfully removed landfill gas from the unsaturated zone (Richgels, 2000).

Before landfill gas control systems are used for groundwater corrective action, site-specific demonstrations are necessary to demonstrate that landfill gas is a source of the contamination. Otherwise, a gas control system would not provide a benefit toward cleaning up the contaminated groundwater. In addition, most conventional landfill gas control systems have been constructed primarily for explosive gas control and power production, and not to remediate groundwater that has been degraded by VOCs, so they may not be effective for remediation purposes. If groundwater corrective action is to become part of the function, then the system should be reevaluated and adjusted or expanded as needed.

Surface water control

Landfills are potential sources of sediment and other pollutants that can impact surface waters. There have been several notable cases of discharges to surface water from landfills in northern California that resulted in significant environmental problems and enforcement actions. Examples include, the Gopher Hill Landfill in Plumas County, where 93,000 gallons of leachate were discharged from a breached impoundment to surface waters in 1989, and the Corinda Los Trancos (Ox Mtn.) Landfill, San Mateo County, where storm water ponds gave way during heavy rains in October 1992 resulting in a large sediment discharge to surface waters and temporary closure of State Highway 92. Case histories of other drainage and erosion problems at landfills in California are summarized in Anderson et al. (1998).

Landfill gas monitoring and control

Detection of explosive levels of landfill gas in structures, utilities, or probes beneath inhabitable off-site properties is rare but can be potentially catastrophic. There have been cases in northern California where construction workers have been injured or killed as a result of uncontrolled landfill gas migration from pre-1991 landfills. The CIWMB tracks violations and publishes an inventory of facilities in violation every 6 months. As of October 1999, there were 11 northern California landfills on the

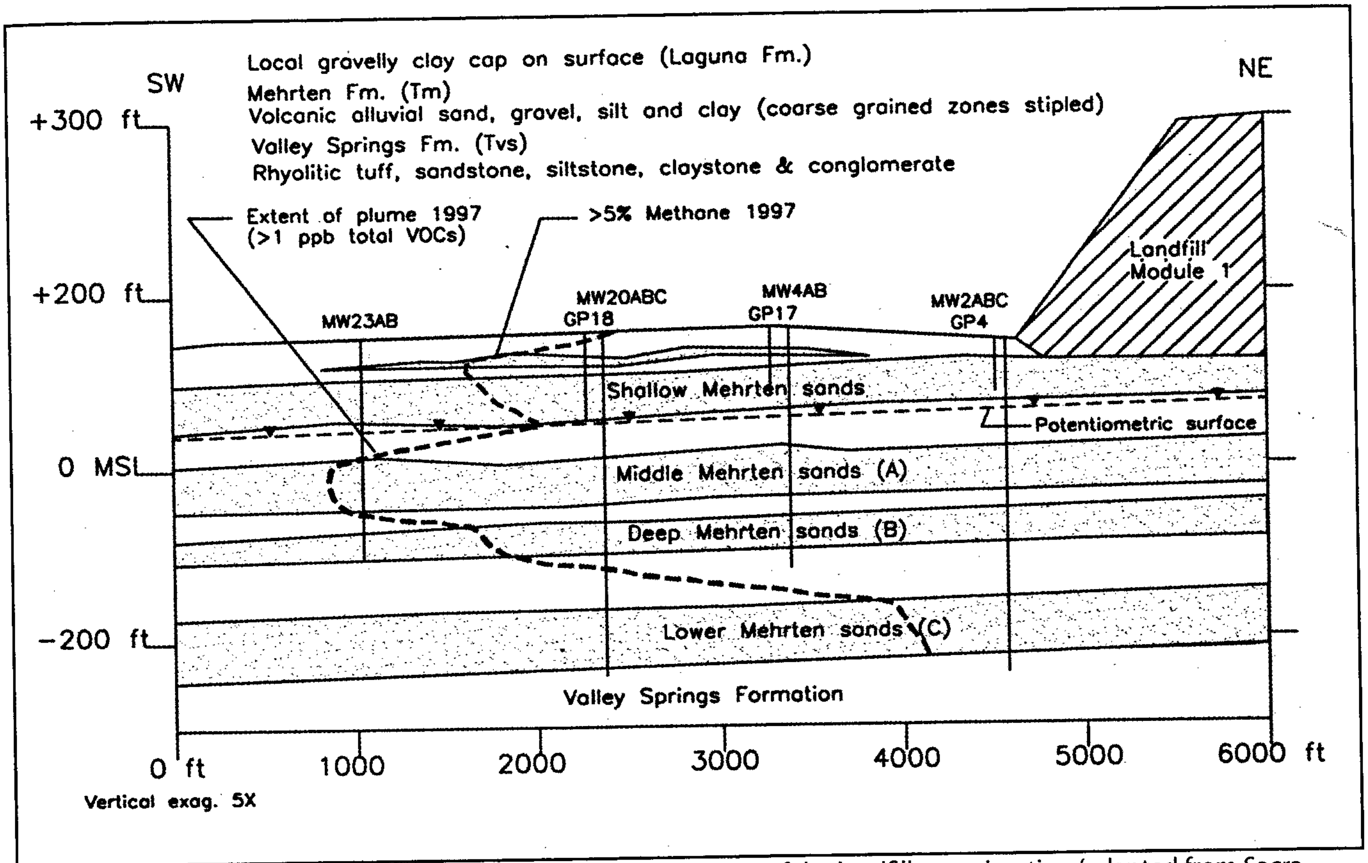

Figure 4. Geologic section of the Keifer Landfill, showing the extent of the landfill gas migration (adapted from Sacramento County, 1998).

inventory. In addition, approximately 53 landfills in northern California have installed landfill gas control systems (Table 1).

Landfill gas migrates preferentially within relatively permeable granular or fractured natural geologic materials and engineered fill. Conversely, landfill gas may be either trapped or not readily migrate through soil or rock units that have a very low permeability with respect to landfill gas, or permeable units that are saturated with water. Site-specific geologic investigations are, therefore, extremely important to ensure adequate monitoring and control. Kiefer Landfill, Sacramento County, is an example of geologic control of landfill gas migration, both for explosive gases and for trace gases that have contaminated groundwater (Figure 4).

Explosive gases require routine quarterly monitoring to ensure that methane does not exceed the lower explosive limit (5% by volume) at the property boundary, and 25% of the lower explosive limit (1.25% by volume) in any on-site structures. In addition to explosive gases, trace gases commonly found in landfill gas can pose a significant health impact to worker and public health and safety. Landfill gas criteria in California's Subtitle D program include prescriptive requirements for perimeter monitoring probe design, construction, and lateral spacing. Guidance on landfill gas monitoring and control is provided in Anderson (1998), CIWMB (1997), and SWANA (1998, 1997a). To develop a landfill gas subsurface monitoring strategy the engineering geologist needs to consider the following factors:

- Location and monitoring of sensitive receptors (e.g. structures, public use areas)
- Invert elevation and boundaries of the landfill
- Location of off-site landfills and other sites that may be potential sources of landfill gas
- Permeability of the soil or rock adjacent to the landfill, including secondary permeability due to bedding, fractures, joints, or faults
- Location and nature of utility lines and construction fills that could be a conduit for landfill gas
- Depth to groundwater
- Barometric and tidal fluctuations

- Natural occurrence of methane and other gases (e.g., organic soils and sediments, oil or gas fields, asphalt seeps, and geothermal areas)
- Likely constituents of concern for landfill gas (e.g. CH_4, CO, CO_2, H_2S, VOCs)
- Monitoring QA/QC (e.g. field and laboratory methods and equipment to be used)
- Monitoring parameters (pressure, oxygen, temperature).

CLOSURE AND POSTCLOSURE

One of the consequences of Subtitle D has been a significant increase in the number of landfills closing. Approximately 86 landfills statewide and 54 in northern California closed between October 1991 and January 1999. Of the northern California landfills, approximately half have completed closure construction and are certified as closed in accordance with current regulations.

Closure criteria in California's Subtitle D program include prescriptive and performance requirements for final cover systems, time frames for closure activities, certification, deed notation, written preliminary and final closure plans, and financial assurance. Postclosure criteria include inspection, maintenance and monitoring of the landfill during the postclosure maintenance period (minimum of 30 years), written preliminary and final postclosure plans, and financial assurance requirements. Closure and postclosure maintenance plans and the certification of closure must be signed and certified by a registered civil engineer or certified engineering geologist. Partial final closure plans may be submitted for approval for one or more individual closure activities during the active life of the landfill. Partial final closure of an active landfill, where final cover is constructed on portions of the waste fill that have reached final grade (sometimes called "rolling closure") is an increasingly common practice to enhance environmental containment of an active landfill and to reduce the set-aside funding required for financial assurance. In many cases, landfills that ceased operation have not set aside adequate funds to implement closure and postclosure. This has resulted in significant environmental and enforcement problems for California.

Landfill sites are also being closed and remediated by complete or partial removal of wastes for consolidation on-site, or disposal to an off-site facility (clean closure). In some cases, cover soil and other materials are recovered and recycled (landfill mining). The engineering geologist may be involved in development and implementation of clean closure plans, including assessment of the limits of waste and contamination, determination and confirmation of soil cleanup levels, and preparation and implementation of excavation grading plans.

At the Clovis Landfill, Fresno County, landfill mining of an older unlined cell is being conducted as a corrective action measure for groundwater contamination and explosive gas control. Soil is screened and recovered for use as daily cover for an active lined cell that is the repository for the excavated residual wastes. McCourtney Road Landfill, Nevada County, completed a clean closure project successfully where building demolition burn ash waste from an unlined cell was removed and consolidated on-site. Clean closure and on-site consolidation of older landfill sites are remedial action alternatives being implemented at several closing military bases (e.g. Mather Air Force Base, Sacramento County).

Cost estimates for closure and postclosure

Third party cost estimates for closure and postclosure maintenance must be calculated on a detailed site-specific basis. However, statewide average cost estimates based on CIWMB records (through 1998) can be summarized based on landfill footprint acreage (closure and postclosure), final cover type (only closure), and removal of outliers that reflect extreme site-specific conditions (Table 7). Cost estimates for clean closure projects can be summarized on a per-cubic-yard-removed basis.

Postclosure land use

Closed landfills are increasingly being developed for further use in northern California, especially for the older pre-Subtitle D sites in urban areas. Engineering geologists may play an integral role in the incorporation of these further use projects into final closure and postclosure maintenance plans. For example, closed landfills can be excellent sites for solid waste transfer stations and recycling facilities because of the existing solid waste infrastructure. Commercial, industrial, golf course, and park developments are also options that are being implemented successfully. CIWMB (1998) provides guidance and information on specific disposal site postclosure land use projects and applicable regulations.

Component	Final cover system	Estimate per waste footprint acre	Standard deviation and range
Postclosure maintenence (30-years)	All	$75,000	$46,000 ($20,000 - $200,000)
Closure	Alternative earthen	$50,000	$21,000 ($9,000 - $90,000)
	Compacted clay (CCL)	$65,000	$25,000 ($25,000 - $125,000)
	Geomembrane (GM) or geosynthetic clay (GCL)	$90,000	$29,000 ($50,000 - $200,000)
	Composite (GM/CCL)	$110,000	$35,000 ($50,000 - $200,000)
	Combination systems	$85,000	$34,000 ($40,000 - $200,000)
Landfill gas control systems (active-flare)	All	$15,000 - $25,000 (+15%)	NA
Clean closure	Range - $10 per cubic yard (Mather Air Force Base) to $40 per cubic yard (McCourtney Road Landfill White Metals Area)		

Table 7. Average closure and postclosure maintenance cost estimates for California landfills (1998 dollars).

SUMMARY

Municipal solid waste landfills ultimately depend on natural geologic conditions to function for their intended purpose. Therefore, engineering geology plays a fundamental role from the inception of the project, through the design and construction stages, and unto the closure and post-closure use of the land. The practice of engineering geology in Northern California on landfill projects is enhanced by knowledge and understanding of case histories and the specific aspects of engineering geology that apply to landfills. Specific engineering geology aspects of landfills summarized in this paper include the regulatory framework, landfill siting, design and construction, alternative earthen final covers, seismic performance, slope and foundation stability, landfill gas monitoring and control, surface water control, groundwater monitoring and corrective action, groundwater contamination by landfill gas, and closure and postclosure maintenance. We hope that this overview will assist engineering geologists, both experienced and new, engaged in landfill projects.

DISCLAIMER

This manuscript does not necessarily reflect the views of the State of California, the California Environmental Protection Agency, or the California Seismic Safety Commission. No official endorsement should be inferred.

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